PRIMORDIAL BLACK HOLES AND EARLY COSMOLOGY

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We describe the changes to the standard primordial black hole constraints on density perturbations if there are modifications to the standard cosmology between the time of formation and nucleosynthesis.

1 Introduction

Primordial black holes (PBHs) provide an important constraint on the physics of the very early Universe. They may form with masses low enough for Hawking evaporation to be important, which gives them a lifetime

$$\frac{\tau}{10^{17}\,\mathrm{sec}} \simeq \left(\frac{M}{10^{15}\,\mathrm{grams}}\right)^3 . \qquad (1)$$

From this we learn that a PBH of initial mass $M \sim 10^{15}$g will evaporate at the present epoch, while another interesting mass is $M \sim 10^9$g which leads to evaporation around nucleosynthesis. Evaporations of PBHs at these times are strongly constrained.

Several mechanisms have been proposed which might lead to PBH formation; the simplest is collapse from large-amplitude, short-wavelength density perturbations. They will form with approximately the horizon mass

$$M_{\rm HOR} \simeq 10^{18}\,\mathrm{g}\left(\frac{10^7\,\mathrm{GeV}}{T}\right)^2 , \qquad (2)$$

which tells us that the PBHs for which evaporation is important must have formed during very early stages of the Universe's evolution. The reason why the constraints are typically so strong is that after formation black holes redshift away as non-relativistic matter. In the standard cosmology the Universe is radiation dominated at these times, and so the energy density in black holes grows, relative to the total, proportionally to the scale factor a.

The purpose of this article is to emphasize that the constraints obtained depend not just on the formation rate and time of the black holes, but on the complete cosmological history. It has recently been fashionable to consider alternatives to the standard cosmology, especially in the interval between about

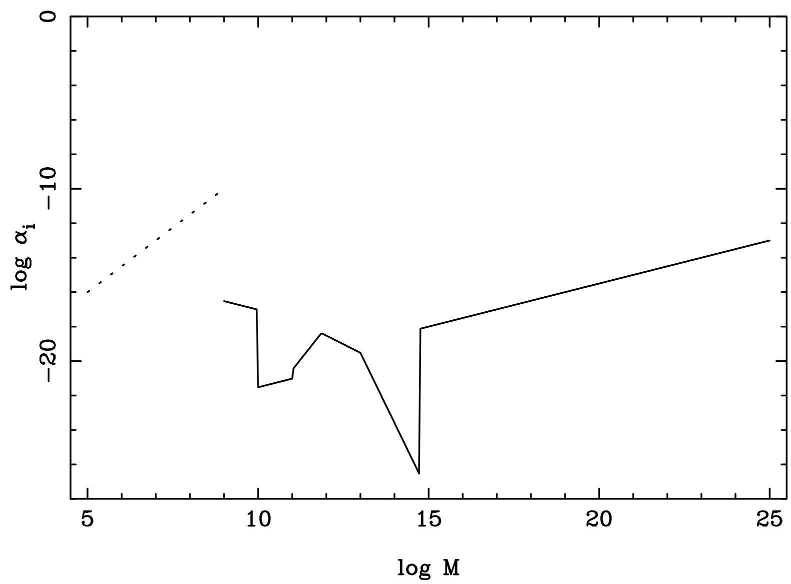

Figure 1: Here α is the fraction of black holes permitted to form. The dotted line assumes black hole evaporation leaves a relic, and is optional.

10^7 GeV and nucleosynthesis. We have studied two such possibilities, a Universe with thermal inflation[1] and one with a prolonged period of matter domination at early times, as well as re-examining the standard cosmology. Here we summarize the results, which have been reported in full in two papers.[2,3]

The three different cosmological histories we study are as follows. In the standard cosmology we begin with inflation (which generates the density perturbations), which gives way through pre/reheating to radiation domination and eventually matter domination. The thermal inflation cosmology introduces a short period of inflation during the radiation-dominated era. Finally, the moduli-dominated scenario inserts a period of moduli domination, the moduli behaving like non-relativistic matter, during the radiation era.

2 The standard cosmology

The many limits [4,2] on the black hole abundance in different mass ranges are shown in Fig. 1. Typically no more than about 10^{-20} of the mass of the Universe can go into PBHs. This limits the size of density perturbations on the relevant mass scale. The minimum mass which can form is governed by

the reheat temperature after inflation.

One way of using these constraints is to consider power spectra normalized to the COBE observations, which probe $M \sim 10^{56}$g. The simplest example is to consider power-law spectra with a constant spectral index n across all relevant scales. (Note that some hybrid inflation models predict n constant even to very short scales.)

The interesting situation is $n > 1$, for which the shortest-scale perturbations dominate, and this was explored by Carr et al. [5] We have redone their analysis and corrected two significant errors. First, they used an incorrect scaling of the horizon mass during the radiation era, which should read

$$\sigma_{\rm hor} = \sigma_{\rm hor}(M_{\rm eq}) \left(\frac{M}{M_{\rm eq}}\right)^{(1-n)/4} . \qquad (3)$$

Secondly, their COBE normalization was incorrect (too low) by a factor of around twenty. With these corrections, the constraint on n tightens considerably,[2] to become $n \lesssim 1.25$, rather than the 1.4 to 1.5 they quoted.

3 With thermal inflation

We model thermal inflation as occurring from $T = 10^7$ GeV down to the supersymmetry scale $T = 10^3$ GeV, then reheating back up to 10^7 GeV. As we have seen, most of the interesting mass region contains PBHs forming before $T = 10^7$ GeV, which implies that the constraints are affected by thermal inflation. Three effects are important:

- Dilution of black holes during thermal inflation.
- A change in the correspondence of scales: COBE scales leave the horizon closer to the end of inflation.
- A mass range which enters the horizon before thermal inflation, but leaves again during it. No new perturbations are generated on this scale during thermal inflation, so from the horizon mass formula we find a missing mass range between 10^{18}g and 10^{26}g in which black holes won't form. Thermal inflation at higher energy could exclude masses below 10^{15}g.

The dilution effect is shown in Fig. 2; typical constraints now lie around 10^{-10} rather than 10^{-20}. Taking all the effects into account,[2] the constraint on the spectral index weakens to $n \lesssim 1.3$.

4 Cosmologies with moduli domination

Another alternative is a prolonged early period of matter domination.[3] For example, moduli fields may dominate, and in certain parameter regimes can

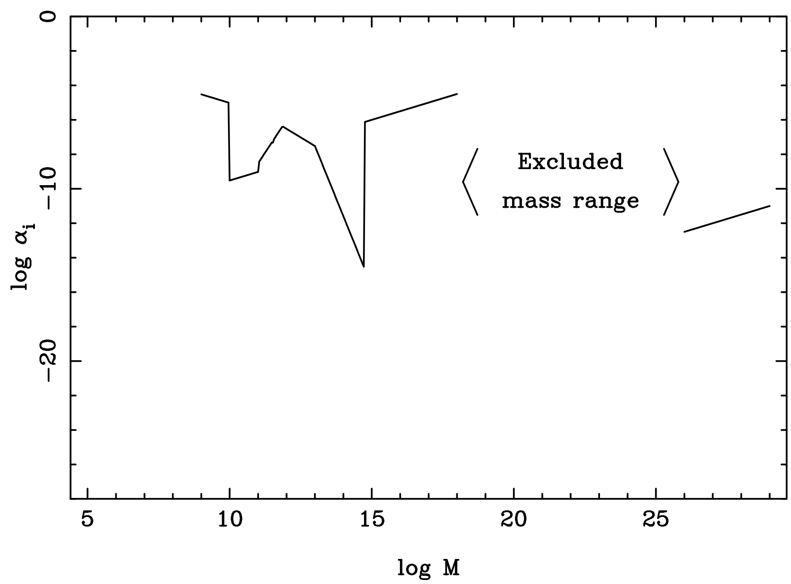

Figure 2: PBH constraints modified to include thermal inflation.

decay before nucleosynthesis. Various assumptions are possible; here we'll assume moduli domination as soon as they start to oscillate (around 10^{11} GeV). Part of the interesting range of PBH masses forms during moduli domination rather than radiation domination. Fig. 3 shows the constraints in this case, and with moduli domination the limit on n again weakens[3] to $n \lesssim 1.3$.

5 Conclusions

Although PBH constraints are an established part of modern cosmology, they are sensitive to the entire cosmological evolution. In the standard cosmology, a power-law spectrum is constrained to $n < 1.25$, presently the strongest observational constraint on n from any source. Alternative cosmological histories can weaken this to $n < 1.30$, and worst-case non-gaussianity [6] can weaken this by another 0.05 or so, though hybrid models giving constant n give gaussian perturbations. Finally, we note that while the impact of the cosmological history on the density perturbation constraint is quite modest due to the exponential formation rate, the change can be much more significant for other formation mechanisms.

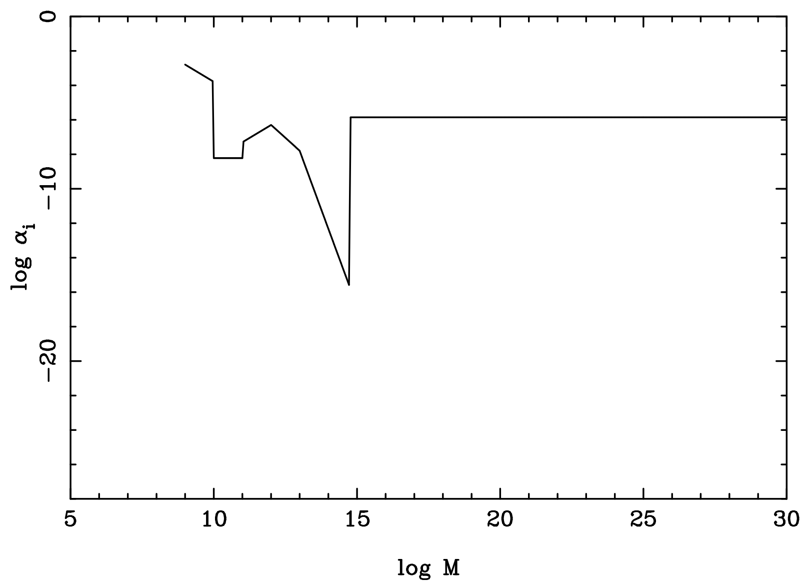

Figure 3: PBH constraints modified for prolonged moduli domination.

Acknowledgments

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